AI reveals unexpected new physics in dusty plasma

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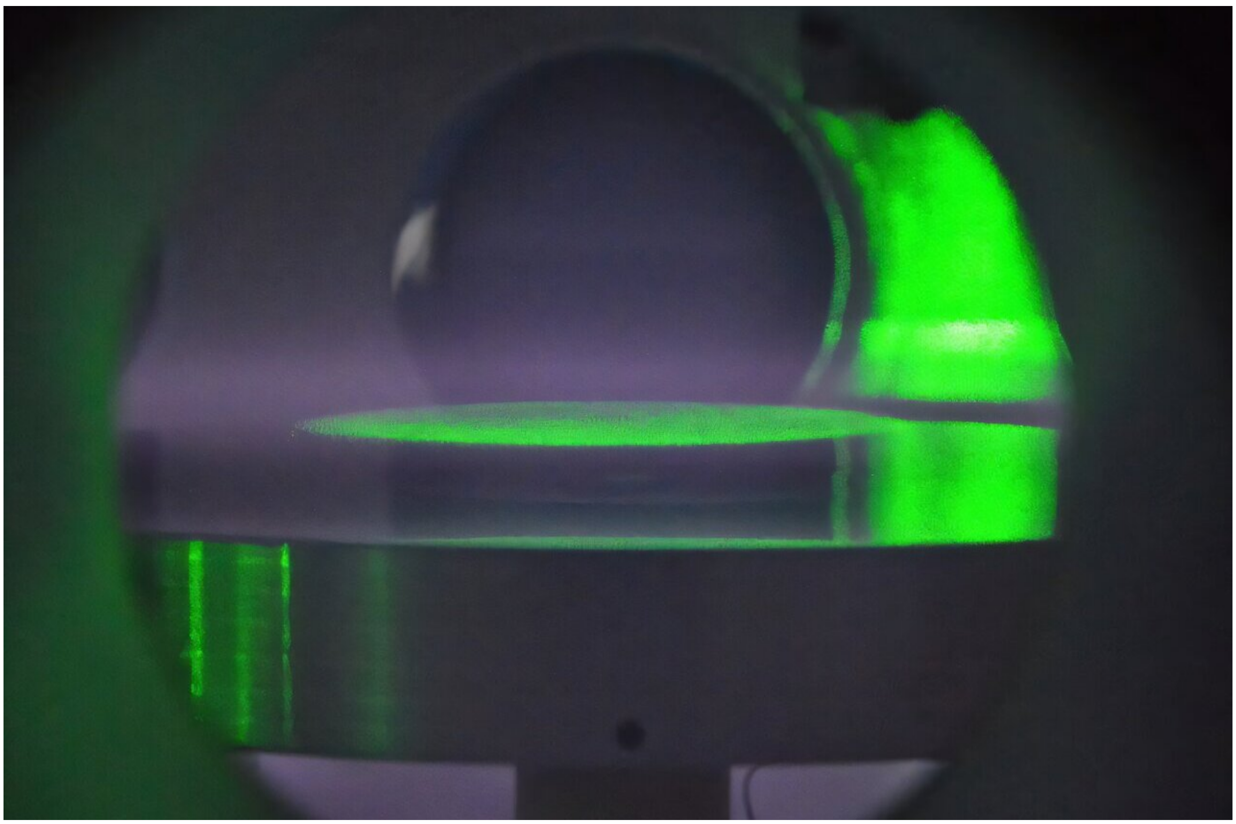


A view inside the laboratory vacuum chamber, where collodial particles are suspended in a flat disc, lit by the green light of a laser, to study dusty plasma. Credit: Burton lab

Physicists have used a machine-learning method to identify surprising new twists on the non-reciprocal forces governing a many-body system.

The journal *Proceedings of the National Academy of Sciences* published the findings by experimental and theoretical physicists at Emory University, based on a neural network model and data from laboratory experiments on dusty plasma—ionized gas containing suspended dust particles.

The work is one of the relatively few instances of using AI not as a data processing or predictive tool, but to discover new physical laws governing the natural world.

"We showed that we can use AI to discover new physics," says Justin Burton, an Emory professor of experimental physics and senior co-author of the paper. "Our AI method is not a black box: we understand how and why it works. The framework it provides is also universal. It could potentially be applied to other many-body systems to open new routes to discovery."

The *PNAS* paper provides the most detailed description yet for the physics of a dusty plasma, yielding precise approximations for non-reciprocal forces.

"We can describe these forces with an accuracy of more than 99%," says Ilya Nemenman, an Emory professor of theoretical physics and co-senior author of the paper.

"What's even more interesting is that we show that some common theoretical assumptions about these forces are not quite accurate. We're able to correct these inaccuracies because we can now see what's occurring in such exquisite detail."

The researchers hope that their AI approach will serve as a starting point for inferring laws from the dynamics of a wide range of many-body systems, which are composed of a large number of interacting particles.

Examples range from colloids—such as paint, ink and other industrial materials—to clusters of cells in living organisms.

First author of the paper is Wentao Yu who worked on the project as an Emory Ph.D. student and is now a postdoctoral fellow at the California Institute of Technology. Co-author is Eslam Abdelaleem, who was also part of the project as an Emory graduate student and is now a postdoctoral fellow at Georgia Tech.

"This project serves as a great example of an interdisciplinary collaboration where the development of new knowledge in plasma physics and AI may lead to further advances in the study of living systems," says Vyacheslav (Slava) Lukin, program director for the NSF Plasma Physics program. "The dynamics of these complex systems is dominated by collective interactions that emerging AI techniques may help us to better describe, recognize, understand and even control."

Plasmas are ionized gases, meaning charged particles of electrons and ions move about freely, creating unique properties like electrical conductivity. Known as the fourth state of matter, plasma makes up an estimated 99.9% of the visible universe, from the solar winds flowing from the sun's corona to lightning bolts that strike Earth.

Dusty plasma, which adds charged particles of dust to the mix of ions and electrons, is also common in space and planetary environments—from the rings of Saturn to Earth's ionosphere.

The charged particles levitating above the surface of the moon, due to weak gravity, are an example of a dusty plasma. "That's why when astronauts walk on the moon their suits get covered in dust," Burton explains.

An example of a dusty plasma on Earth can occur during wildfires when soot mixes with the smoke. The charged soot particles can interfere with radio signals, affecting communications between firefighters.

Burton studies the physics of dusty plasmas and amorphous materials. His lab conducts experiments on tiny, plastic particles suspended in a vacuum chamber filled with plasma as a model for more complex systems. By altering the gas pressure inside the chamber, the lab members can mimic the properties of real phenomena and study how a system changes when it is driven by forces.

For the current project, Burton and Yu developed a tomographic-imaging technique to track the three-dimensional (3D) motion of particles in a dusty plasma. A laser spread into a sheet of light moves up and down in the vacuum chamber as a high-speed camera captures images. The snapshots of particles within the plane of light are then assembled into a stack, revealing the 3D location of individual particles over centimeter length scales for several minutes.

A theoretical biophysicist, Nemenman searches for laws that underlie natural dynamical systems, especially complex biological ones. He's interested in particular in the phenomenon of collective motion, such as how human cells move about the body.

"General questions of how a whole system arises from interactions of tiny parts are very important," Nemenman explains. "In cancer, for instance, you want to understand how the interaction of cells may relate to some of them breaking away from a tumor and moving to a new place, becoming metastatic."

While Nemenman often collaborates with researchers from the life sciences, the project with the Burton lab offered a chance to delve into a system somewhat simpler than a living one. That presented an ideal chance to try to use AI to investigate the dynamics of collective motion to learn new physics.

"For all the talk about how AI is revolutionizing science, there are very few examples where something fundamentally new has been found directly by an AI system," Nemenman says.

One of the most famous examples of AI, ChatGPT, trains on the vast amount of information available on the internet in order to predict the appropriate text in response to a prompt.

"When you're probing something new, you don't have a lot of data to train AI," Nemenman explains. "That meant we would have to design a neural network that could be trained with a small amount of data and still learn something new."

Burton, Nemenman, Yu and Abdelaleem met weekly in a conference room to discuss the problem.

"We needed to structure the network to follow the necessary rules while still allowing it to explore and infer unknown physics," Burton explains.

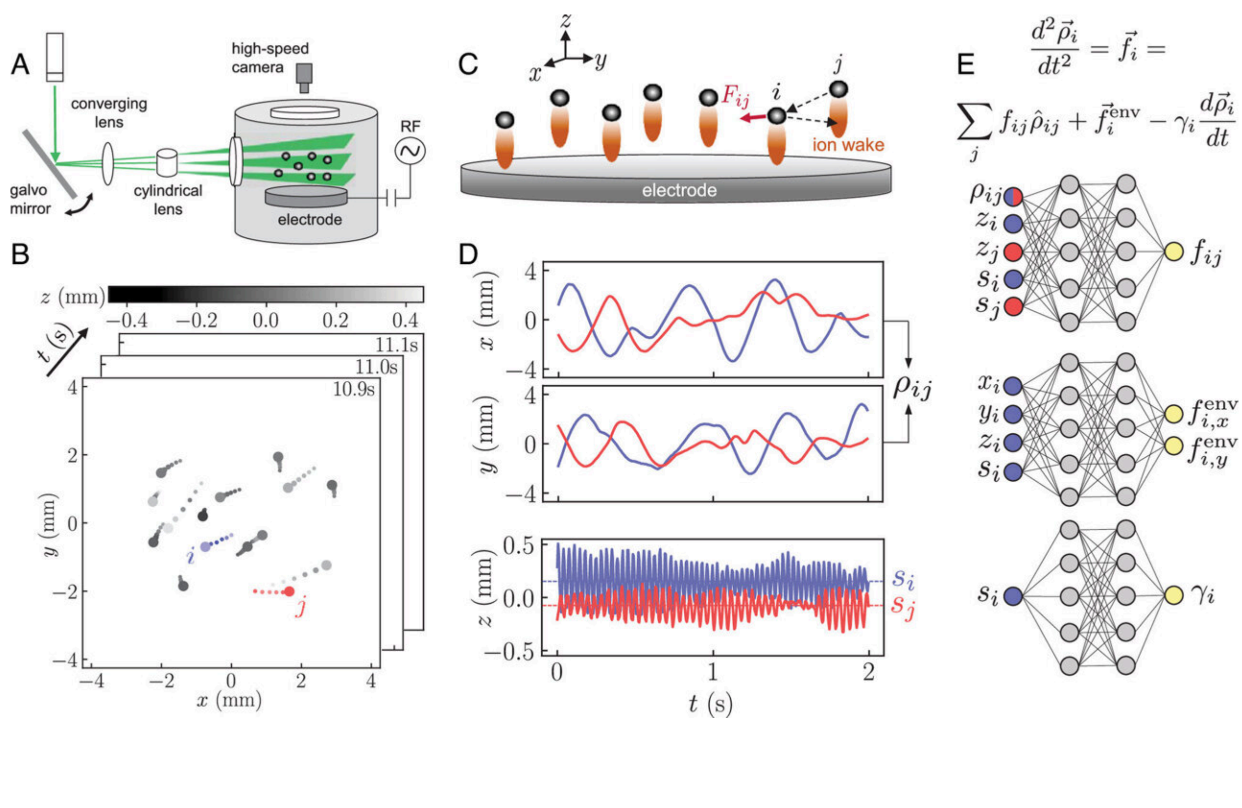
"It took us more than a year of back-and-forth discussions in these weekly meetings," Nemenman adds. "Once we came up with the correct structure of the network to train, it turned out to be fairly simple."

The physicists distilled the restraints for the neural network to modeling three independent contributions to particle motion: the effect of velocity, or drag force; the environmental forces, such as gravity; and the particle-to-particle forces.

Trained on 3D particle trajectories, the AI model accounted for inherent symmetries, non-identical particles and learned the effective non-reciprocal forces between particles with exquisite accuracy.

To explain these non-reciprocal forces, the researchers use the analogy of two boats moving across a lake, creating waves. The wake pattern of each boat affects the motion of the other boat. The wake of one boat may repel or attract the other boat depending on their relative positions—for example, whether the boats are traveling side by side or one behind the other.

"In a dusty plasma, we described how a leading particle attracts the trailing particle, but the trailing particle always repels the leading one," Nemenman explains. "This phenomenon was expected by some but now we have a precise approximation for it which didn't exist previously."



Overview of experiment and data workflow. Credit: *Proceedings of the National Academy of Sciences* (2025). DOI: 10.1073/pnas.2505725122, https://www.pnas.org/doi/10.1073/pnas.2505725122

Their findings also correct some wrong assumptions about dusty plasma.

For example, a longstanding theory held that the larger the radius of a dust particle, the larger the charge that stuck to that particle, in exact proportion to the radius of the particle. "We showed that this theory is not quite right," Nemenman says. "While it's true that the larger the particle the larger the charge, that increase is not necessarily proportional to the radius. It depends on the density and temperature of the plasma."

Another theory held that the forces between two particles falls off exponentially in direct relationship to the distance between two particles and that the factor by which it drops is not dependent on the size of the particle. The new AI method showed that the drop off in force does depend on the particle size.

The researchers verified their findings through experiments.

Their physics-based neural network runs on a desktop computer and offers a universal, theoretical framework to unravel mysteries about other complex, many-body systems.

Nemenman, for example, is looking forward to an upcoming visiting professorship at the Konstanz School of Collective Behavior in Germany. The school brings together interdisciplinary approaches to study the burgeoning field of collective behavior, everything from flocking birds to schools of fish and human crowds.

"I'll be teaching students from all over the world how to use AI to infer the physics of collective motion—not within a dusty plasma but within a living system," he says.

While their AI framework holds the ability to infer new physics, expert human physicists are needed to design the right structure for the neural network and to interpret and to validate the resulting data.

"It takes critical thinking to develop and use AI tools in ways that make real advances in science, technology and the humanities," Burton says.

He feels optimistic about the potential for AI to benefit society.

"I think of it like the Star Trek motto, to boldly go where no one has before," Burton says. "Used properly, AI can open doors to whole new realms to explore."

More information: Physics-tailored machine learning reveals unexpected physics in dusty plasmas, *Proceedings of the National Academy of Sciences* (2025). DOI: 10.1073/pnas.2505725122, www.pnas.org/doi/10.1073/pnas.2505725122

Provided by Emory University

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